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Observation of s-channel production of single top quarks at the Tevatron

CDF Collaboration ; Canelli, F ; Kilminster, B ; et al

Abstract: We report the first observation of single-top-quark production in the s channel through the combination of the CDF and D0 measurements of the cross section in proton-antiproton collisions at a center-of-mass energy of 1.96 TeV. The data correspond to total integrated luminosities of up to 9.7 fb⁻¹ per experiment. The measured cross section is $\sigma_s = 1.29^{+0.26}_{-0.24}$ pb. The probability of observing a statistical fluctuation of the background to a cross section of the observed size or larger is 1.8×10^{-10} , corresponding to a significance of 6.3 standard deviations for the presence of an s-channel contribution to the production of single-top quarks.

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Observation of s -channel production of single top quarks at the Tevatron

T. Aaltonen^{†,21} V.M. Abazov^{†,13} B. Abbott^{†,116} B.S. Acharya^{†,80} M. Adams^{†,98} T. Adams^{†,97} J.P. Agnew^{†,94} G.D. Alexeev^{†,13} G. Alkhazov^{†,88} A. Alton^{†ii,31} S. Amerio^{†vv,39} D. Amidei^{†,31} A. Anastassov^{†v,15} A. Annovi^{†,17} J. Antos^{†,12} G. Apollinari^{†,15} J.A. Appel^{†,15} T. Arisawa^{†,52} A. Artikov^{†,13} J. Asaadi^{†,47} W. Ashmanskas^{†,15} A. Askew^{†,97} S. Atkins^{†,106} B. Auerbach^{†,2} K. Augsten^{†,62} A. Aurisano^{†,47} C. Avila^{†,60} F. Azfar^{†,38} F. Badaud^{†,65} W. Badgett^{†,15} T. Bae^{†,25} L. Bagby^{†,15} B. Baldin^{†,15} D.V. Bandurin^{†,51} S. Banerjee^{†,80} A. Barbaro-Galtieri^{†,26} E. Barberis^{†,107} P. Baringer^{†,105} V.E. Barnes^{†,43} B.A. Barnett^{†,23} P. Barria^{†xx,41} J.F. Bartlett^{†,15} P. Bartos^{†,12} U. Bässler^{†,70} M. Baucé^{†vv,39} V. Bazterra^{†,98} A. Bean^{†,105} F. Bedeschi^{†,41} M. Begalli^{†,57} S. Behari^{†,15} L. Bellantoni^{†,15} G. Bellettini^{†ww,41} J. Bellinger^{†,54} D. Benjamin^{†,14} A. Beretvas^{†,15} S.B. Beri^{†,78} G. Bernardi^{†,69} R. Bernhard^{†,74} I. Bertram^{†,92} M. Besançon^{†,70} R. Beuselinck^{†,93} P.C. Bhat^{†,15} S. Bhatia^{†,108} V. Bhatnagar^{†,78} A. Bhatti^{†,45} K.R. Bland^{†,5} G. Blazey^{†,99} S. Blessing^{†,97} K. Bloom^{†,109} B. Blumenfeld^{†,23} A. Bocci^{†,14} A. Bodek^{†,44} A. Boehnlein^{†,15} D. Boline^{†,113} E.E. Boos^{†,86} G. Borissov^{†,92} D. Bortoletto^{†,43} M. Borysova^{†tt,91} J. Boudreau^{†,42} A. Boveia^{†,11} A. Brandt^{†,119} O. Brandt^{†,75} L. Brigliadori^{†uu,6} R. Brock^{†,32} C. Bromberg^{†,32} A. Bross^{†,15} D. Brown^{†,69} E. Brucken^{†,21} X.B. Bu^{†,15} J. Budagov^{†,13} H.S. Budd^{†,44} M. Buehler^{†,15} V. Buescher^{†,76} V. Bunichev^{†,86} S. Burdin^{†jj,92} K. Burkett^{†,15} G. Busetto^{†vv,39} P. Bussey^{†,19} C.P. Buszello^{†,90} P. Butti^{†ww,41} A. Buzatu^{†,19} A. Calamba^{†,10} E. Camacho-Pérez^{†,83} S. Camarda^{†,4} M. Campanelli^{†,28} F. Canelli^{†cc,11} B. Carls^{†,22} D. Carlsmith^{†,54} R. Carosi^{†,41} S. Carrillo^{†l,16} B. Casal^{†j,9} M. Casarsa^{†,48} B.C.K. Casey^{†,15} H. Castilla-Valdez^{†,83} A. Castro^{†uu,6} P. Catastini^{†,20} S. Caughron^{†,32} D. Cauz^{†ccddd,48} V. Cavaliere^{†,22} M. Cavalli-Sforza^{†,4} A. Cerri^{†e,26} L. Cerrito^{†q,28} S. Chakrabarti^{†,113} K.M. Chan^{†,103} A. Chandra^{†,121} E. Chapon^{†,70} G. Chen^{†,105} Y.C. Chen^{†,1} M. Chertok^{†,7} G. Chiarelli^{†,41} G. Chlachidze^{†,15} K. Cho^{†,25} S.W. Cho^{†,82} S. Choi^{†,82} D. Chokheli^{†,13} B. Choudhary^{†,79} S. Cihangir^{†,15} D. Claes^{†,109} A. Clark^{†,18} C. Clarke^{†,53} J. Clutter^{†,105} M.E. Convery^{†,15} J. Conway^{†,7} M. Cooke^{†ss,15} W.E. Cooper^{†,15} M. Corbo^{†y,15} M. Corcoran^{†,121} M. Cordelli^{†,17} F. Couderc^{†,70} M.-C. Cousinou^{†,67} C.A. Cox^{†,7} D.J. Cox^{†,7} M. Cremonesi^{†,41} D. Cruz^{†,47} J. Cuevas^{†x,9} R. Culbertson^{†,15} D. Cutts^{†,118} A. Das^{†,95} N. d'Ascenzo^{†u,15} M. Datta^{†ff,15} G. 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 F. Margaroli^{†,46} P. Marino^{†yy,41} J. Martínez-Ortega^{†,83} M. Martínez^{†,4} K. Matera^{†,22} M.E. Mattson^{†,53}
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S. Yang^{‡, 59} T. Yang^{†, 15} U.K. Yang^{†, 25} Y.C. Yang^{†, 25} W.-M. Yao^{†, 26} T. Yasuda^{‡, 15} Y.A. Yatsunenko^{‡, 13}
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S.W. Youn^{‡, 15} G.B. Yu^{†, 14} I. Yu^{†, 25} J.M. Yu^{‡, 31} A.M. Zanetti^{†, 48} Y. Zeng^{†, 14} J. Zennaro^{‡, 112} T.G. Zhao^{‡, 94}
B. Zhou^{‡, 31} C. Zhou^{†, 14} J. Zhu^{†, 31} M. Zielinski^{‡, 44} D. Zieminska^{‡, 101} L. Zivkovic^{‡, 69} and S. Zucchelli^{†uu6}

(CDF Collaboration)[†]

(D0 Collaboration)^{†, ‡}

¹*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*

²*Argonne National Laboratory, Argonne, Illinois 60439, USA*

³*University of Athens, 157 71 Athens, Greece*

⁴*Institut de Física d'Altes Energies, ICREA, Universitat Autònoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*

⁵*Baylor University, Waco, Texas 76798, USA*

⁶*Istituto Nazionale di Fisica Nucleare Bologna, ^{uu}University of Bologna, I-40127 Bologna, Italy*

⁷*University of California, Davis, Davis, California 95616, USA*

⁸*University of California, Los Angeles, Los Angeles, California 90024, USA*

⁹*Instituto de Física de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*

¹⁰*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*

¹¹*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*

¹²*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*

¹³*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*

¹⁴*Duke University, Durham, North Carolina 27708, USA*

¹⁵*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*

¹⁶*University of Florida, Gainesville, Florida 32611, USA*

¹⁷*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*

¹⁸*University of Geneva, CH-1211 Geneva 4, Switzerland*

¹⁹*Glasgow University, Glasgow G12 8QQ, United Kingdom*

²⁰*Harvard University, Cambridge, Massachusetts 02138, USA*

²¹*Division of High Energy Physics, Department of Physics, University of Helsinki, FIN-00014, Helsinki, Finland; Helsinki Institute of Physics, FIN-00014, Helsinki, Finland*

²²*University of Illinois, Urbana, Illinois 61801, USA*

²³*The Johns Hopkins University, Baltimore, Maryland 21218, USA*

²⁴*Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany*

²⁵*Center for High Energy Physics: Kyungpook National University,*

Daegu 702-701, Korea; Seoul National University, Seoul 151-742,

Korea; Sungkyunkwan University, Suwon 440-746,

Korea; Korea Institute of Science and Technology Information,

Daejeon 305-806, Korea; Chonnam National University,

Gwangju 500-757, Korea; Chonbuk National University, Jeonju 561-756,

Korea; Ewha Womans University, Seoul, 120-750, Korea

²⁶*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

²⁷*University of Liverpool, Liverpool L69 7ZE, United Kingdom*

²⁸*University College London, London WC1E 6BT, United Kingdom*

²⁹*Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain*

³⁰*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

³¹*University of Michigan, Ann Arbor, Michigan 48109, USA*

³²*Michigan State University, East Lansing, Michigan 48824, USA*

³³*Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia*

³⁴*University of New Mexico, Albuquerque, New Mexico 87131, USA*

³⁵*The Ohio State University, Columbus, Ohio 43210, USA*

³⁶*Okayama University, Okayama 700-8530, Japan*

³⁷*Osaka City University, Osaka 558-8585, Japan*

³⁸*University of Oxford, Oxford OX1 3RH, United Kingdom*

³⁹*Istituto Nazionale di Fisica Nucleare, Sezione di Padova, ^{vv}University of Padova, I-35131 Padova, Italy*

⁴⁰*University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*

- ⁴¹Istituto Nazionale di Fisica Nucleare Pisa, ^{ww}University of Pisa,
^{xx}University of Siena, ^{yy}Scuola Normale Superiore,
 I-56127 Pisa, Italy, ^{zz}INFN Pavia, I-27100 Pavia,
 Italy, ^{aaa}University of Pavia, I-27100 Pavia, Italy
- ⁴²University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
- ⁴³Purdue University, West Lafayette, Indiana 47907, USA
- ⁴⁴University of Rochester, Rochester, New York 14627, USA
- ⁴⁵The Rockefeller University, New York, New York 10065, USA
- ⁴⁶Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1,
^{bbb}Sapienza Università di Roma, I-00185 Roma, Italy
- ⁴⁷Mitchell Institute for Fundamental Physics and Astronomy,
 Texas A&M University, College Station, Texas 77843, USA
- ⁴⁸Istituto Nazionale di Fisica Nucleare Trieste, ^{ccc}Gruppo Collegato di Udine,
^{ddd}University of Udine, I-33100 Udine, Italy, ^{eee}University of Trieste, I-34127 Trieste, Italy
- ⁴⁹University of Tsukuba, Tsukuba, Ibaraki 305, Japan
- ⁵⁰Tufts University, Medford, Massachusetts 02155, USA
- ⁵¹University of Virginia, Charlottesville, Virginia 22906, USA
- ⁵²Waseda University, Tokyo 169, Japan
- ⁵³Wayne State University, Detroit, Michigan 48201, USA
- ⁵⁴University of Wisconsin, Madison, Wisconsin 53706, USA
- ⁵⁵Yale University, New Haven, Connecticut 06520, USA
- ⁵⁶LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
- ⁵⁷Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
- ⁵⁸Universidade Federal do ABC, Santo André, Brazil
- ⁵⁹University of Science and Technology of China, Hefei, People's Republic of China
- ⁶⁰Universidad de los Andes, Bogotá, Colombia
- ⁶¹Charles University, Faculty of Mathematics and Physics,
 Center for Particle Physics, Prague, Czech Republic
- ⁶²Czech Technical University in Prague, Prague, Czech Republic
- ⁶³Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
- ⁶⁴Universidad San Francisco de Quito, Quito, Ecuador
- ⁶⁵LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France
- ⁶⁶LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3,
 Institut National Polytechnique de Grenoble, Grenoble, France
- ⁶⁷CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
- ⁶⁸LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
- ⁶⁹LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France
- ⁷⁰CEA, Irfu, SPP, Saclay, France
- ⁷¹IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
- ⁷²IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France
- ⁷³III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
- ⁷⁴Physikalisches Institut, Universität Freiburg, Freiburg, Germany
- ⁷⁵II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
- ⁷⁶Institut für Physik, Universität Mainz, Mainz, Germany
- ⁷⁷Ludwig-Maximilians-Universität München, München, Germany
- ⁷⁸Panjab University, Chandigarh, India
- ⁷⁹Delhi University, Delhi, India
- ⁸⁰Tata Institute of Fundamental Research, Mumbai, India
- ⁸¹University College Dublin, Dublin, Ireland
- ⁸²Korea Detector Laboratory, Korea University, Seoul, Korea
- ⁸³CINVESTAV, Mexico City, Mexico
- ⁸⁴Nikhef, Science Park, Amsterdam, the Netherlands
- ⁸⁵Radboud University Nijmegen, Nijmegen, the Netherlands
- ⁸⁶Moscow State University, Moscow, Russia
- ⁸⁷Institute for High Energy Physics, Protvino, Russia
- ⁸⁸Petersburg Nuclear Physics Institute, St. Petersburg, Russia
- ⁸⁹Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d'Altes Energies (IFAE), Barcelona, Spain
- ⁹⁰Uppsala University, Uppsala, Sweden
- ⁹¹Taras Shevchenko National University of Kyiv, Kiev, Ukraine
- ⁹²Lancaster University, Lancaster LA1 4YB, United Kingdom
- ⁹³Imperial College London, London SW7 2AZ, United Kingdom
- ⁹⁴The University of Manchester, Manchester M13 9PL, United Kingdom
- ⁹⁵University of Arizona, Tucson, Arizona 85721, USA
- ⁹⁶University of California Riverside, Riverside, California 92521, USA

- ⁹⁷Florida State University, Tallahassee, Florida 32306, USA
⁹⁸University of Illinois at Chicago, Chicago, Illinois 60607, USA
⁹⁹Northern Illinois University, DeKalb, Illinois 60115, USA
¹⁰⁰Northwestern University, Evanston, Illinois 60208, USA
¹⁰¹Indiana University, Bloomington, Indiana 47405, USA
¹⁰²Purdue University Calumet, Hammond, Indiana 46323, USA
¹⁰³University of Notre Dame, Notre Dame, Indiana 46556, USA
¹⁰⁴Iowa State University, Ames, Iowa 50011, USA
¹⁰⁵University of Kansas, Lawrence, Kansas 66045, USA
¹⁰⁶Louisiana Tech University, Ruston, Louisiana 71272, USA
¹⁰⁷Northeastern University, Boston, Massachusetts 02115, USA
¹⁰⁸University of Mississippi, University, Mississippi 38677, USA
¹⁰⁹University of Nebraska, Lincoln, Nebraska 68588, USA
¹¹⁰Rutgers University, Piscataway, New Jersey 08855, USA
¹¹¹Princeton University, Princeton, New Jersey 08544, USA
¹¹²State University of New York, Buffalo, New York 14260, USA
¹¹³State University of New York, Stony Brook, New York 11794, USA
¹¹⁴Brookhaven National Laboratory, Upton, New York 11973, USA
¹¹⁵Langston University, Langston, Oklahoma 73050, USA
¹¹⁶University of Oklahoma, Norman, Oklahoma 73019, USA
¹¹⁷Oklahoma State University, Stillwater, Oklahoma 74078, USA
¹¹⁸Brown University, Providence, Rhode Island 02912, USA
¹¹⁹University of Texas, Arlington, Texas 76019, USA
¹²⁰Southern Methodist University, Dallas, Texas 75275, USA
¹²¹Rice University, Houston, Texas 77005, USA
¹²²University of Washington, Seattle, Washington 98195, USA
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We report the first observation of single-top-quark production in the s channel through the combination of the CDF and D0 measurements of the cross section in proton-antiproton collisions at a center-of-mass energy of 1.96 TeV. The data correspond to total integrated luminosities of up to 9.7 fb^{-1} per experiment. The measured cross section is $\sigma_s = 1.29_{-0.24}^{+0.26} \text{ pb}$. The probability of observing a statistical fluctuation of the background to a cross section of the observed size or larger is 1.8×10^{-10} , corresponding to a significance of 6.3 standard deviations for the presence of an s -channel contribution to the production of single-top quarks.

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The top quark, with a mass of $m_t = 173.2 \pm 0.9 \text{ GeV}$ [1], is the most massive and one of the most puzzling elementary particles of the standard model (SM). Detailed studies of top-quark production and decay provide powerful tests of strong and electroweak interactions, as well as sensitivity to physics beyond the standard model (BSM) [2]. At the Tevatron, where protons (p) and antiprotons (\bar{p}) collide at a center-of-mass energy of $\sqrt{s} = 1.96 \text{ TeV}$, top quarks are produced predominantly in pairs ($t\bar{t}$) via the strong interaction [3]. Top quarks are also produced singly in $p\bar{p}$ collisions via the electroweak interaction. The single-top-quark production cross section is expected to be proportional to the square of the magnitude of the quark-mixing Cabibbo-Kobayashi-Maskawa matrix [4] element V_{tb} , and consequently sensitive to potential contributions from a fourth generation of quarks [5, 6], as well as flavor-changing neutral currents [7–10], anomalous top-quark couplings [11–13], heavy W' bosons [14–17], supersymmetric charged Higgs bosons [18, 19], or other new phenomena [20, 21].

At the Tevatron, there are two important processes in which a single top quark is produced in association with

other quarks. The dominant channel proceeds through the exchange of a space-like virtual W boson between a light quark and a bottom quark (b quark) in the t channel [22–24]. A second mode occurs through the exchange of a time-like virtual W boson in the s channel, which produces a top quark and a b quark [25]. Figure 1 shows the leading Feynman diagrams for the s - and t -channel production modes. Independent measure-

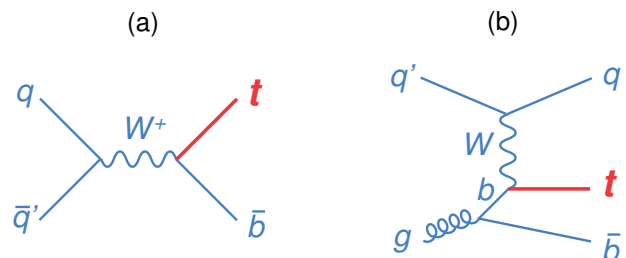


FIG. 1: Dominant Feynman diagrams for (a) s -channel and (b) t -channel single-top-quark production at the Tevatron.

ments of s -channel and t -channel production are important, since BSM contributions could have different effects on the two modes [20].

Single-top-quark production, independent of channel, was reported by the CDF and D0 collaborations in Refs. [26, 27] and [28, 29], respectively. The D0 collaboration subsequently measured with larger data sets the production cross section for the combined s and t channels [30], and obtained $\sigma_{s+t} = 4.11^{+0.59}_{-0.55}$ pb using a data set of 9.7 fb^{-1} in agreement with the SM prediction of 3.15 ± 0.19 pb ($m_t = 172.5 \text{ GeV}$) [24, 31].

After establishing the $s + t$ process, the cross sections of the individual production modes were measured independently. Several differences in the properties of s - and t -channel events can be used to distinguish them from one another. Events originating from t -channel production typically contain one light-flavor jet in the forward detector region (at large pseudorapidity), which is useful for distinguishing them from events associated with s -channel production and other SM background processes. Moreover, events from the s -channel process are more likely to contain two jets originating from b quarks (b jets) within the central region of the detector where they can be identified. Hence, single-top-like events with two identified b jets are more likely to have originated from s -channel production. Exploiting these differences, the D0 collaboration observed the t -channel process [32], and measured its cross section to be $\sigma_t = 2.90 \pm 0.59$ pb. This compares to the SM prediction of 2.10 ± 0.13 pb ($m_t = 172.5 \text{ GeV}$) [24]. At the CERN LHC proton-proton collider, t -channel production was also observed by the ATLAS and CMS collaborations [33, 34].

Observing the s -channel process is more difficult, since the expected cross section is smaller than that of the t channel and its kinematic features are less distinct from the background. However, the Tevatron has an advantage over the LHC in this mode, since valence quarks ($q\bar{q}'$ from $p\bar{p}$) generally initiate s -channel single-top-quark production, leading to a larger signal-to-background ratio at the Tevatron than at the LHC. Due to this advantage, the CDF and D0 collaborations have reported evidence for s -channel production independently of each other [30, 35], while the LHC experiments have to date reported only unpublished upper limits on the cross section.

In this Letter, we report a combination of s -channel cross section analyses performed by the CDF [35, 36] and D0 [30] collaborations. The CDF and D0 detectors are central magnetic spectrometers surrounded by electromagnetic and hadronic calorimeters and muon detectors [37–39]. The combined measurement utilizes the full Tevatron Run II data sets corresponding to up to 9.7 fb^{-1} of integrated luminosity per experiment.

The data are selected using a logical OR of many on-line selection requirements which preserve high signal efficiency for offline analysis. Since the magnitude of the W -

top-bottom quark coupling is much larger than the W -top-down and W -top-strange quark couplings [40], each top quark decays almost exclusively to a W boson and a b quark. The selection is split into two distinct final-state topologies, both designed to select single-top-quark events in which the W boson decays leptonically.

One final-state topology (ℓ +jets), analyzed by both collaborations, contains single-top-quark events in which the W boson decays leptonically ($W \rightarrow \ell\nu_\ell$). We select events that (i) contain only one isolated lepton ($\ell = e$ or μ) with large transverse momentum p_T , (ii) have large missing transverse energy \cancel{E}_T [39], (iii) have either two jets (CDF analysis) or two or three jets (D0 analysis) with large p_T , and (iv) have one or two b jets. To identify b jets, multivariate techniques are used that discriminate b jets from jets originating from light quarks and gluons [41, 42]. Additional selection criteria are applied to exclude kinematic regions that are difficult to model, and to minimize the quantum chromodynamics (QCD) multijet background where one jet is misreconstructed as a lepton and spurious \cancel{E}_T arises from jet energy mismeasurements.

The other final-state topology, analyzed by the CDF collaboration, involves \cancel{E}_T and jets, but no reconstructed isolated charged leptons (\cancel{E}_T +jets). The CDF analysis avoids overlap with the ℓ +jets sample by explicitly vetoing events with identified leptons [36]. Large missing transverse energy is required and events with two or three reconstructed jets are accepted. This additional sample increases the acceptance for s -channel signal events by encompassing those in which the W -boson decay produces a muon or electron that is either not reconstructed or not isolated, or a hadronically decaying tau lepton that is reconstructed as a third jet. After the basic event selection, QCD multijet events dominate the \cancel{E}_T +jets event sample. To reduce this multijet background, a neural-network event selection is optimized to preferentially select signal-like events.

Events passing the ℓ +jets and \cancel{E}_T +jets selections are further separated into independent analysis channels based on the number of reconstructed jets as well as the number and quality of b -tagged jets. Each of the analyzed channels has a different background composition and signal (s) to background (b) ratio. Analyzing them separately enhances the sensitivity to single-top-quark production [30, 35, 36].

Both collaborations use Monte Carlo (MC) generators to simulate the kinematic properties of signal and background events, except in the case of multijet production, for which the model is derived from data. The CDF analysis models single-top-quark signal events at next-to-leading-order (NLO) accuracy in the strong coupling constant α_s using the POWHEG [43] generator. The D0 analysis uses the SINGLETOP [44] event generator, based on NLO COMPHEP calculations that match the event kinematic features predicted by NLO calculations [45, 46].

Spin information in the decays of the top quark and the W boson is preserved for both POWHEG and SINGLETOP.

Kinematic properties of background events associated with the W +jets and Z +jets processes are simulated using the ALPGEN leading-order MC generator [47], and those of diboson processes (WW , WZ and ZZ) are modeled using PYTHIA [48]. The $t\bar{t}$ process is modeled using PYTHIA in the CDF analysis and by ALPGEN in the D0 analysis. Higgs-boson processes are modeled using simulated events generated with PYTHIA for a Higgs-boson mass of $m_H = 125$ GeV. The D0 analysis models the distributions and their shape uncertainties of the WH production process in the 2-jet, 2- b -tag channel using simulated single-top-quark t -channel events that have been shown to have the same distribution of the discriminant output and to be only a small contamination to the s -channel signal. In all cases PYTHIA is used to model proton remnants and simulate the hadronization of all generated partons. The mass of the top quark in simulated events is set to $m_t = 172.5$ GeV, which is consistent with the current Tevatron average value [1]. All MC events are processed through GEANT-based detector simulations [49] and reconstructed by the same software packages used for the collider data.

Predictions for the normalization of simulated background-process contributions are estimated using both simulation and data. Data are used to normalize the W plus light-flavor and heavy-flavor jet contributions using enriched W +jets data samples that have negligible signal content [27, 30, 36]. All other simulated background samples are normalized to the theoretical cross sections at NLO combined with next-to-next-to-leading log (NNLL) resummation [24] for t -channel single-top-quark production, at next-to-NLO [50] for $t\bar{t}$, at NLO [51] for Z +jets and diboson production, and including all relevant higher-order QCD and electroweak corrections for Higgs-boson production [52]. Differences observed between simulated events and data in lepton and jet reconstruction efficiencies, resolutions, jet-energy scale (JES), and b -tagging efficiencies are adjusted in the simulation to match the data, through correction functions obtained from measurements in independent data samples.

We form multivariate discriminants, optimized for separating the s -channel single-top-quark signal events in each of the analysis samples from the larger background contributions, to extract the cross section measurements [53]. The combined cross section measurement is obtained using a Bayesian statistical analysis of the observed discriminant distributions from each sample, comparing data to the modeled distributions for each of the contributing signal and background processes [54].

A complete list of systematic uncertainties for the ℓ +jets analyses is given in Tab. I. These can arise from uncertainties on differential distributions (Dist) and their normalizations (Norm). The CDF \cancel{E}_T +jets analysis has a similar set of systematic uncertainties that are taken

as fully correlated with the CDF ℓ +jets analysis except for the uncertainty related to the data-based background. Sources of systematic uncertainty common to measurements of both collaborations are assumed to be 100% correlated, while other uncertainties are assumed to be uncorrelated. The categories of uncertainty correspond generally to those in Ref. [1, 3], and can be summarized as follows:

Detector-specific luminosity uncertainty: The component of the uncertainty on luminosity that comes from the uncertainty on the acceptance and efficiency of the luminosity detector is taken as uncorrelated between the CDF [55] and D0 [56] measurements.

Luminosity from cross section: The portion of the uncertainty in luminosity that comes from uncertainties on the inelastic and diffractive cross sections is fully correlated between the CDF and D0 measurements.

Signal modeling: The systematic uncertainty associated with uncertainties in the modeling of the single-top-quark signal, including uncertainties from the choice of the description of initial- and final-state QCD radiation, and proton and antiproton parton density functions, also covering uncertainties in the applied hadronization models, is taken as fully correlated between the CDF and D0 measurements.

Background from simulation: The systematic uncertainty associated with uncertainties in the modeling of various background contributions is taken as fully correlated between the CDF and D0 measurements. This includes uncertainties in $t\bar{t}$ and diboson process normalizations originating from theoretical calculations.

Background based on data: The systematic uncertainty associated with the modeling of various background sources obtained using data-driven methods is uncorrelated between the CDF and D0 measurements. This includes uncertainties on the normalization of W +jets, $Wb\bar{b}$, and $Wc\bar{c}$ events as well as uncertainties on the modeling of the contributions and discriminant-variable shapes for the W +jets and QCD multijet production processes.

Detector modeling: The systematic uncertainty on efficiencies for identifying reconstructed objects and to cover observed mismodeling of the data from the simulations is uncorrelated between the CDF and D0 measurements.

b -jet tagging: The systematic uncertainty associated with the modeling of b -jet tagging efficiencies and

associated mistag rates is uncorrelated between the CDF [41] and D0 [42] measurements.

Jet energy scale (JES): This systematic uncertainty originates from using calibration-data samples to establish the JES. For the CDF analyses, this corresponds to uncertainties associated with the η -dependent JES corrections, which are estimated using dijet events in data. For the D0 analysis, this includes uncertainties in calorimeter response for light jets, uncertainties from η - and p_T -dependent JES corrections, and other small contributions. This uncertainty is assumed to be uncorrelated between the CDF [57] and D0 [58] measurements.

TABLE I: Systematic uncertainties associated with the CDF and the D0 single-top-quark s -channel cross section measurements in ℓ +jets final states. The values shown for each category indicate the range of uncertainties applied to the predicted normalizations for signal and background contributions over the full set of analysis samples from each experiment. The black dots indicate which categories contribute uncertainties on the shape of the final multivariate discriminant output variable. It is also noted if categories are treated as fully correlated between the two experiments.

Systematic uncertainty	CDF		D0		Correlated
	Norm	Dist	Norm	Dist	
Lumi from detector	4.5%		4.5%		No
Lumi from cross section	4.0%		4.0%		Yes
Signal modeling	2–10%	•	3–8%		Yes
Background (simulation)	2–12%	•	2–11%	•	Yes
Background (data)	15–40%	•	19–50%	•	No
Detector modeling	2–10%	•	1–5%	•	No
b -jet-tagging	10–30%		5–40%	•	No
JES	0–20%	•	0–40%	•	No

The Bayesian posterior probability density as a function of s -channel signal cross section (σ_s) is given by

$$p(\sigma_s) = \int L(\sigma_s, \{\theta\} | \text{data}) \pi(\sigma_s) \Pi(\{\theta\}) d\{\theta\}, \quad (1)$$

where L is the joint binned likelihood function for all channels

$$L = \prod_{i=\text{bins, channels}} \frac{(s_i + b_i)^{n_i} e^{-(s_i + b_i)}}{n_i!}. \quad (2)$$

The number of observed events in bin i is n_i . $\{\theta\}$ is the set of nuisance parameters representing the systematic uncertainties, and $\Pi(\{\theta\})$ is the product of the prior probability densities encoding the systematic uncertainties on $\{\theta\}$. The predictions for the number of signal events s_i and background events b_i depend on the values of the nuisance parameters that are integrated over in

Eq. (1). The prior density for the signal cross section, $\pi(\sigma_s)$, is taken to be a uniform prior for non-negative cross sections. We quote the measured cross section as the value that maximizes its posterior likelihood, and the uncertainty as the smallest interval that contains 68% of the integrated area of the posterior density.

Figure 2 shows the signal and background expectations and the data as a function of $\log_{10}(s/b)$ of the collected bins, for the combined CDF and D0 analyses. The ex-

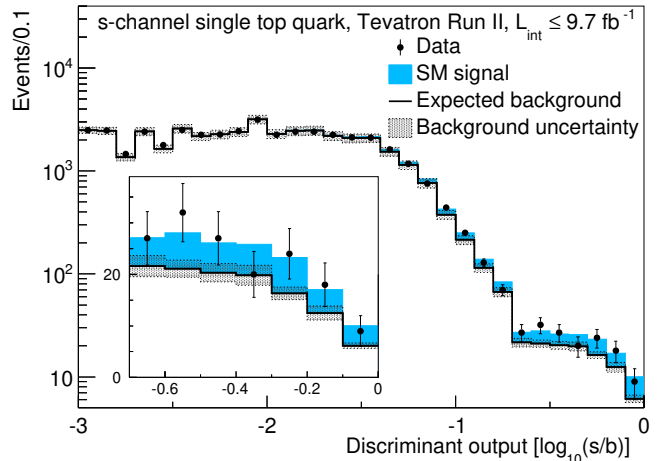


FIG. 2: (Color online) Distribution of the discriminant histograms, summed for bins with similar signal-to-background ratio (s/b). The expected sum of the backgrounds is shown by the unfilled histogram, and the uncertainty of the background is represented by the grey shaded band. The expected s -channel signal contribution is shown by a filled blue histogram.

tracted posterior probability distribution for σ_s is presented in Fig. 3, and Fig. 4 gives a graphical presentation of the individual and combined measurements. All measurements agree within their uncertainties with the SM prediction, $\sigma_s^{SM} = 1.05 \pm 0.06$ pb ($m_t = 172.5$ GeV) [31]. The most probable value for the combined cross section is $\sigma_s = 1.29^{+0.26}_{-0.24}$ pb for a top-quark mass of 172.5 GeV. The total expected uncertainty is 20%, and the expected uncertainty without considering systematic uncertainties is 14%. The dependence of the measured value on the assumed value of the top-quark mass is negligible compared to the uncertainty on the measurement [27, 30].

The statistical significance of this result is quantified through a calculated p -value based on an asymptotic log-likelihood ratio approach (LLR) [59], including systematic uncertainties. The p -value quantifies the probability that the measured value of the cross section or a larger value could result from a background fluctuation in the absence of signal. The distributions of LLR resulting from fits of simulated samples that include background-only, or signal-plus-background, contributions are presented in Fig. 5. The probability to measure an s -channel

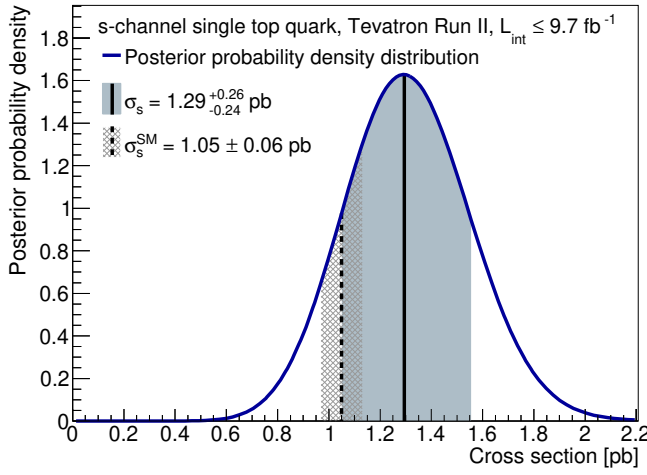


FIG. 3: The posterior probability distribution for the combination of the CDF and D0 analysis channels compared with the NLO+NNLL theoretical prediction [31].

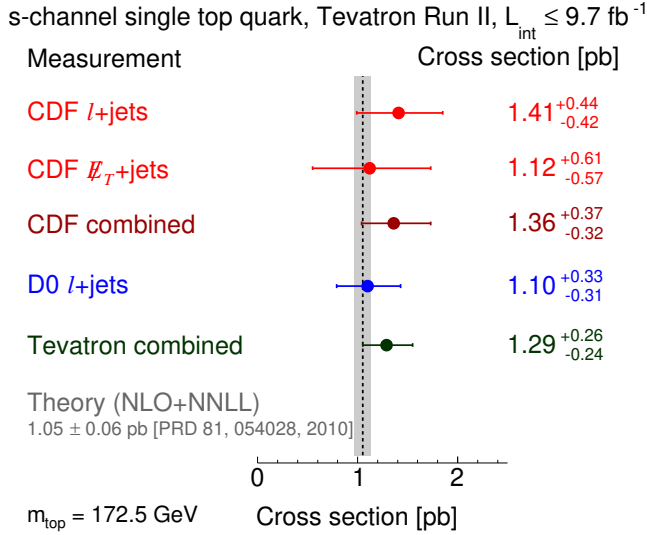


FIG. 4: (Color online) Measured single-top-quark s -channel production cross sections from each of the individual analyses and various combinations of these analyses compared with the NLO+NNLL theoretical prediction [31].

cross section of at least the observed value in the absence of signal is 1.8×10^{-10} , corresponding to a significance of 6.3 standard deviations (s.d.), with a sensitivity expected from the SM of 5.1 s.d.

In summary, we report the first observation of s -channel single-top-quark production with a significance of 6.3 s.d. by combining the CDF and D0 measurements. The combined value of the s -channel single-top-quark production cross section is $\sigma_s = 1.29^{+0.26}_{-0.24}$ pb, in agreement with the SM expectation.

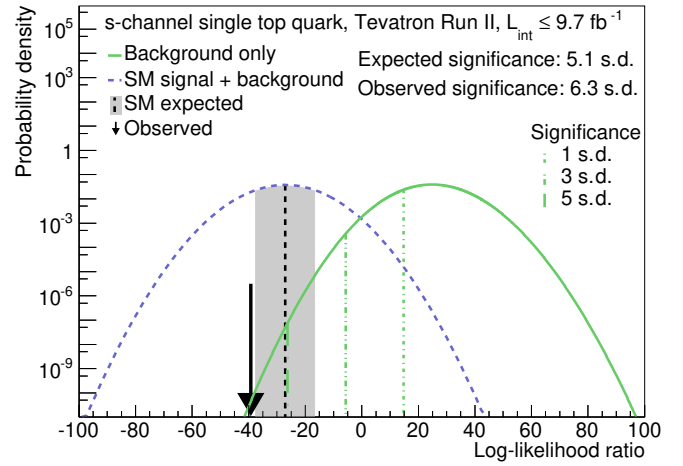


FIG. 5: (Color online) Log-likelihood ratios for the background-only (solid green line) and SM-signal-plus-background (dashed blue) hypotheses from the combined measurement.

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* Deceased

† With visitors from ^aUniversity of British Columbia, Vancouver, BC V6T 1Z1, Canada, ^bIstituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy, ^cUniversity of California Irvine, Irvine, CA 92697, USA, ^dInstitute of Physics, Academy of Sciences of the Czech Republic, 182 21, Czech Republic, ^eCERN, CH-1211 Geneva, Switzerland, ^fCornell University, Ithaca, NY 14853, USA, ^gUniversity of Cyprus, Nicosia CY-1678, Cyprus, ^hOffice of Science, U.S. Department of Energy, Washington, DC 20585, USA, ⁱUniversity College Dublin, Dublin 4, Ireland, ^jETH,

- 8092 Zürich, Switzerland, ^kUniversity of Fukui, Fukui City, Fukui Prefecture, Japan 910-0017, ^lUniversidad Iberoamericana, Lomas de Santa Fe, México, C.P. 01219, Distrito Federal, ^mUniversity of Iowa, Iowa City, IA 52242, USA, ⁿKinki University, Higashi-Osaka City, Japan 577-8502, ^oKansas State University, Manhattan, KS 66506, USA, ^pBrookhaven National Laboratory, Upton, NY 11973, USA, ^qQueen Mary, University of London, London, E1 4NS, United Kingdom, ^rUniversity of Melbourne, Victoria 3010, Australia, ^sMuons, Inc., Batavia, IL 60510, USA, ^tNagasaki Institute of Applied Science, Nagasaki 851-0193, Japan, ^uNational Research Nuclear University, Moscow 115409, Russia, ^vNorthwestern University, Evanston, IL 60208, USA, ^wUniversity of Notre Dame, Notre Dame, IN 46556, USA, ^xUniversidad de Oviedo, E-33007 Oviedo, Spain, ^yCNRS-IN2P3, Paris, F-75205 France, ^zUniversidad Tecnica Federico Santa Maria, 110v Valparaiso, Chile, ^{aa}The University of Jordan, Amman 11942, Jordan, ^{bb}Universite catholique de Louvain, 1348 Louvain-La-Neuve, Belgium, ^{cc}University of Zürich, 8006 Zürich, Switzerland, ^{dd}Massachusetts General Hospital, Boston, MA 02114 USA, ^{ee}Harvard Medical School, Boston, MA 02114 USA, ^{ff}Hampton University, Hampton, VA 23668, USA, ^{gg}Los Alamos National Laboratory, Los Alamos, NM 87544, USA, ^{hh}Università degli Studi di Napoli Federico I, I-80138 Napoli, Italy
- [†] With visitors from ⁱⁱAugustana College, Sioux Falls, SD, USA, ^{jj}The University of Liverpool, Liverpool, UK, ^{kk}DESY, Hamburg, Germany, ^{ll}Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico, ^{mm}SLAC, Menlo Park, CA, USA, ⁿⁿUniversity College London, London, UK, ^{oo}Centro de Investigacion en Computacion - IPN, Mexico City, Mexico, ^{pp}Universidade Estadual Paulista, São Paulo, Brazil, ^{qq}Karlsruher Institut für Technologie (KIT) - Steinbuch Centre for Computing (SCC), ^{rr}Office of Science, U.S. Department of Energy, Washington, D.C. 20585, USA, ^{ss}American Association for the Advancement of Science, Washington, D.C. 20005, USA, ^{tt}National Academy of Science of Ukraine (NASU) - Kiev Institute for Nuclear Research (KINR)
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- and pointing at the i th calorimeter tower. \vec{E}_T is corrected for high-energy muons and for mismeasurements of jet energies. We define $E_T = |\vec{E}_T|$. The transverse momentum p_T is defined to be $p \sin \theta$.
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